Microscale Atmospheric Re-Entry Sensors

Justin A. Atchison
JAA73@Cornell.edu

Cornell University
Space Systems Design Studio

Co-Authors: Zachary R. Manchester
Dr. Mason A. Peck

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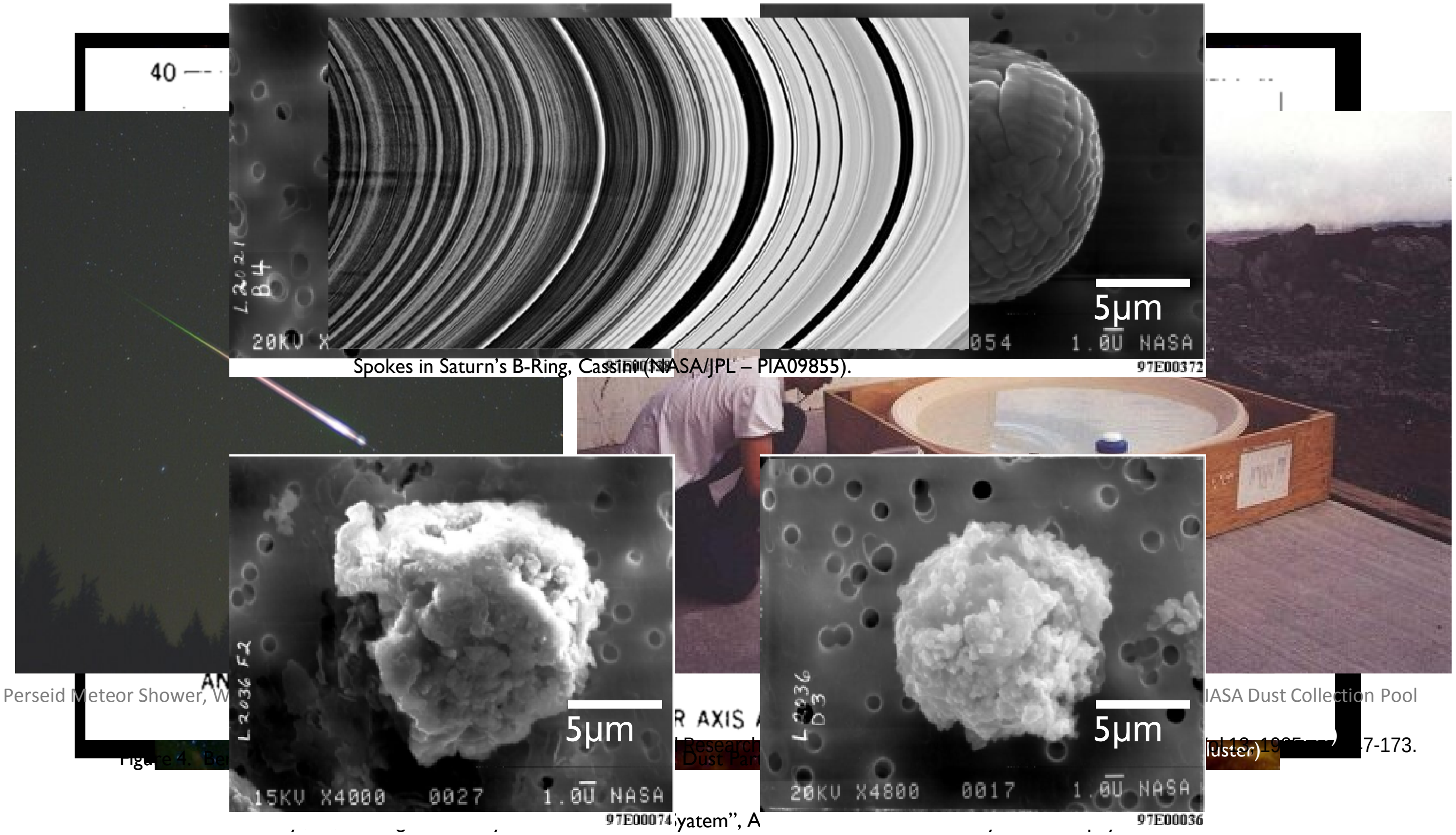
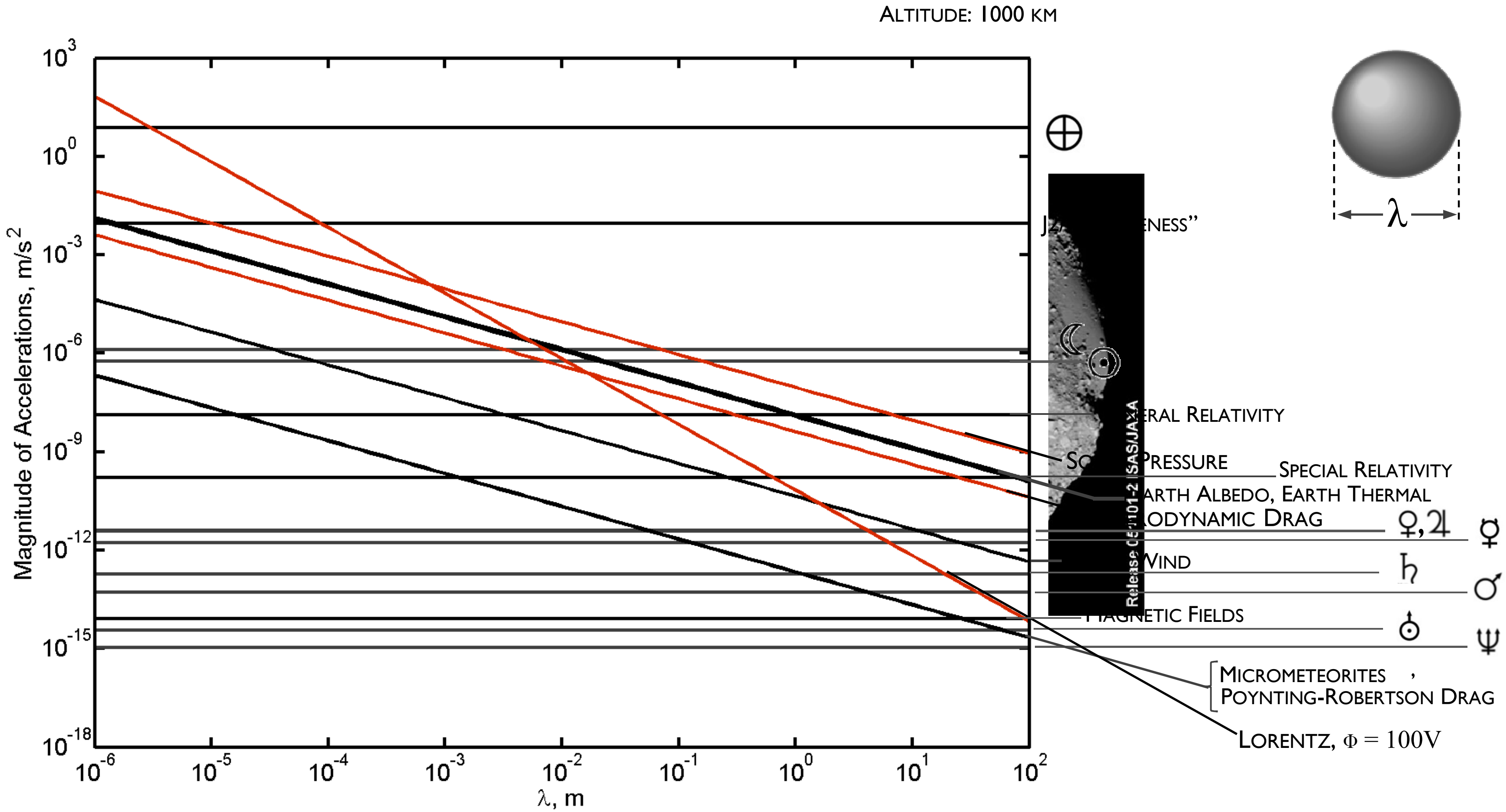
Dust Dynamics

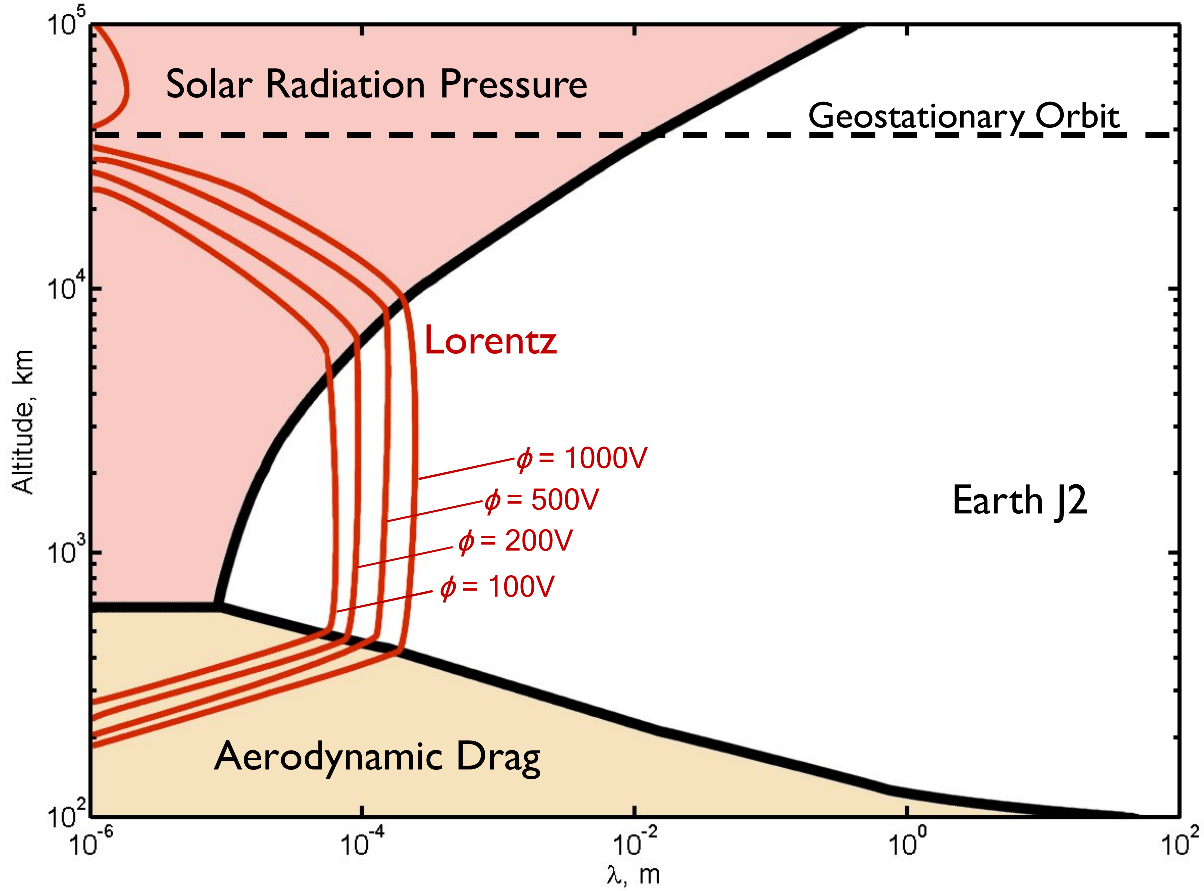


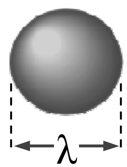
Many Accelerations Depend on Length-Scale



Images Courtesy NASA / JAXA

Length-Scale and Altitude





Area-to-Mass and Characteristic Length

$$a = \frac{F}{m} \propto \frac{A}{m}$$

$$A = \kappa_A \lambda^2$$

$$m = \kappa_V \rho \lambda^3$$

$$\frac{A}{m} = \frac{1}{\rho} \frac{\kappa_A}{\kappa_V} \frac{1}{\lambda}$$

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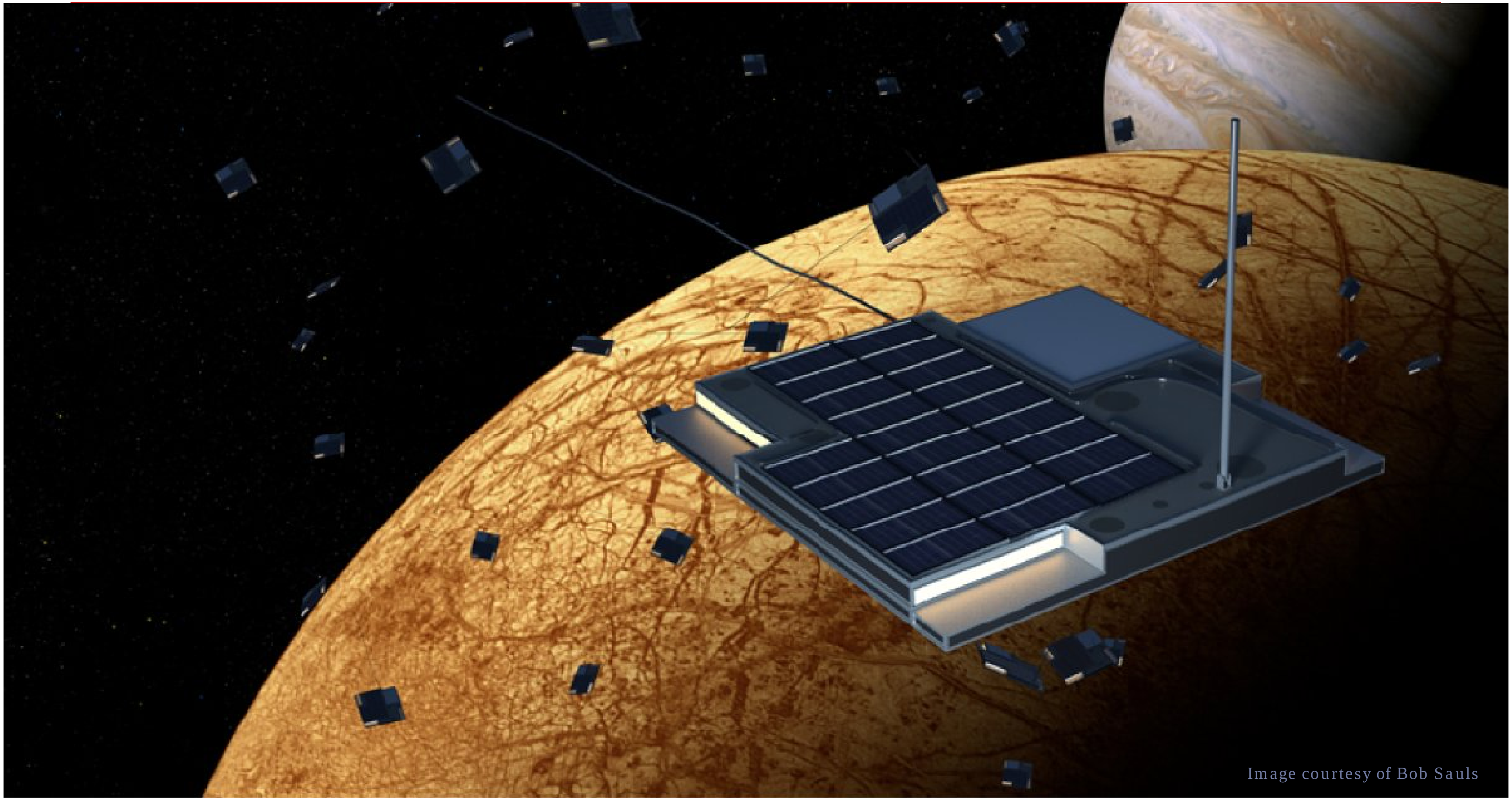
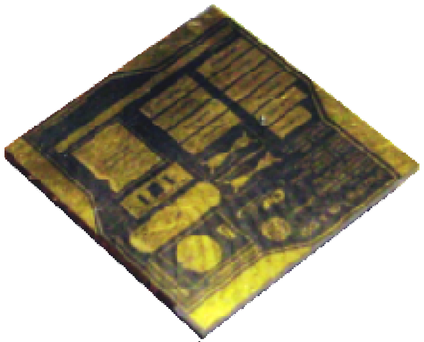


Spacecraft-on-Chip Architecture

- Application specific integrated circuit (ASIC) with spacecraft functionality: power, communications, data handling, etc.
- Extremely thin form factor



$\lambda = 1$ cm
$\varepsilon = 0.0025$
$\rho = 2300$ kg/m^3, Silicon

$A = 1$ cm^2
$m = 8$ mg
$A/m = 125$ m^2/kg
$\beta = 0.036$

Sprite – A small, elusive supernatural being.

Traditional Motivation

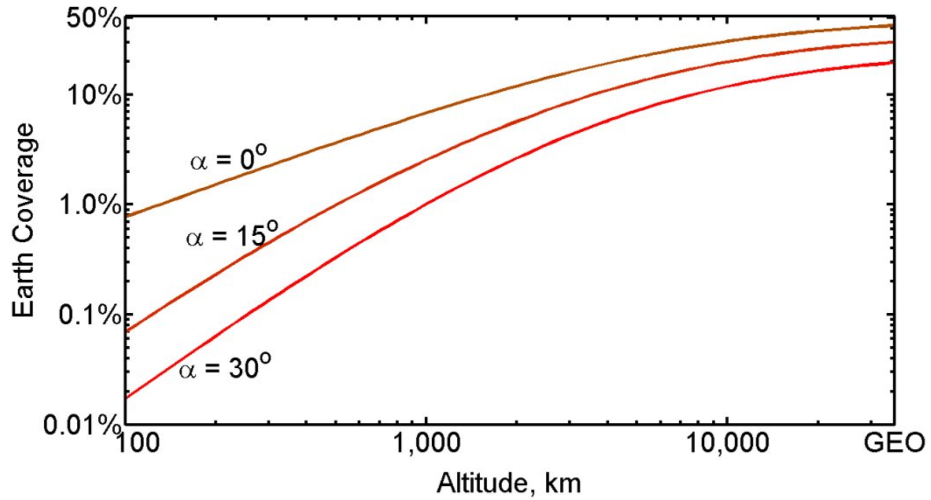
Cost= f (Size, Mass, Power)

New Capabilities

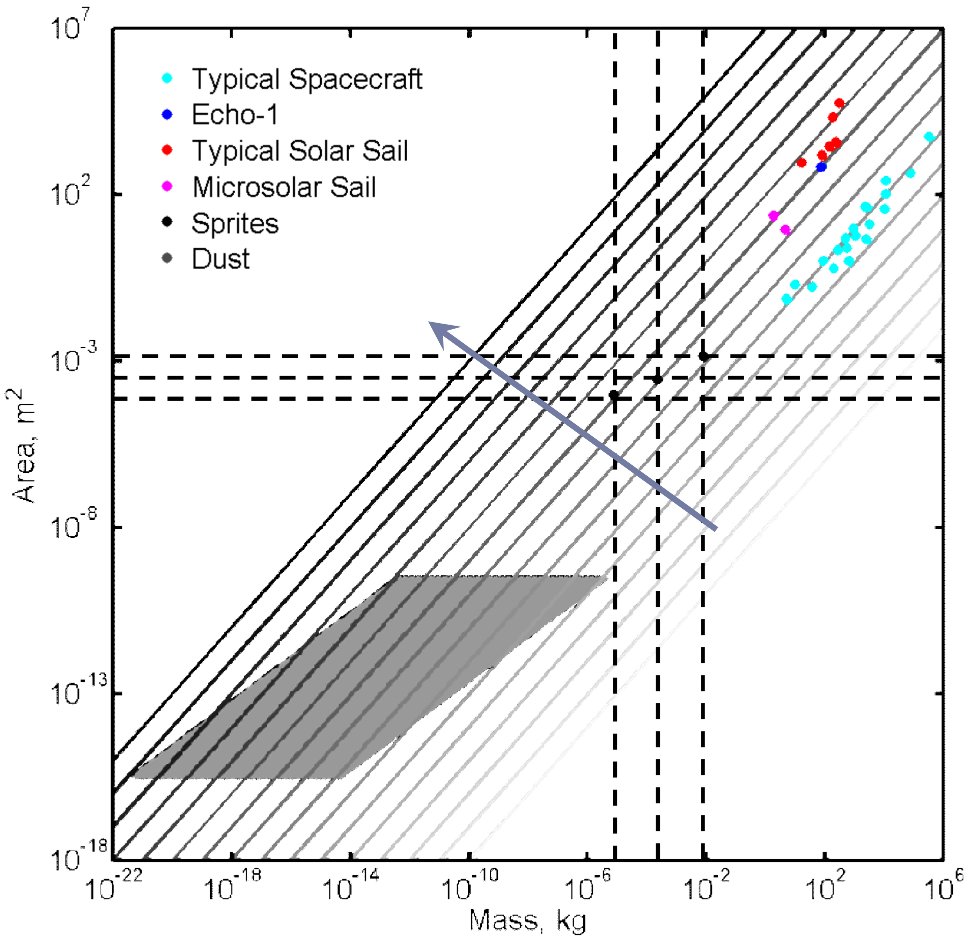
"Can't we make 'Palm Pilot' versions of spacecraft instead of main frames?"

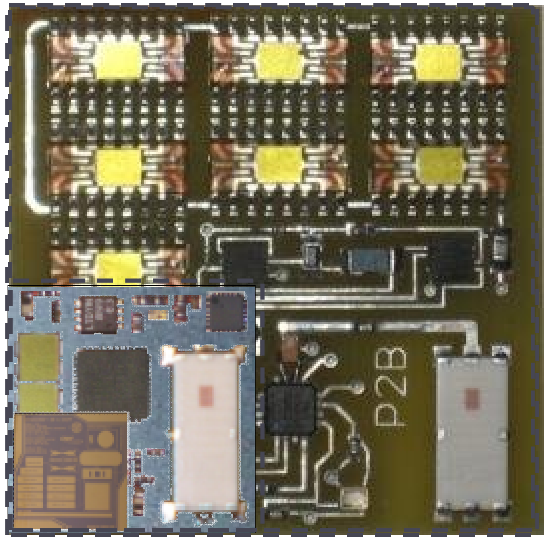
Siegfried W. Janson
Aerospace Corporation, May 2000

Distributed Sensing



Area-to-Mass Survey

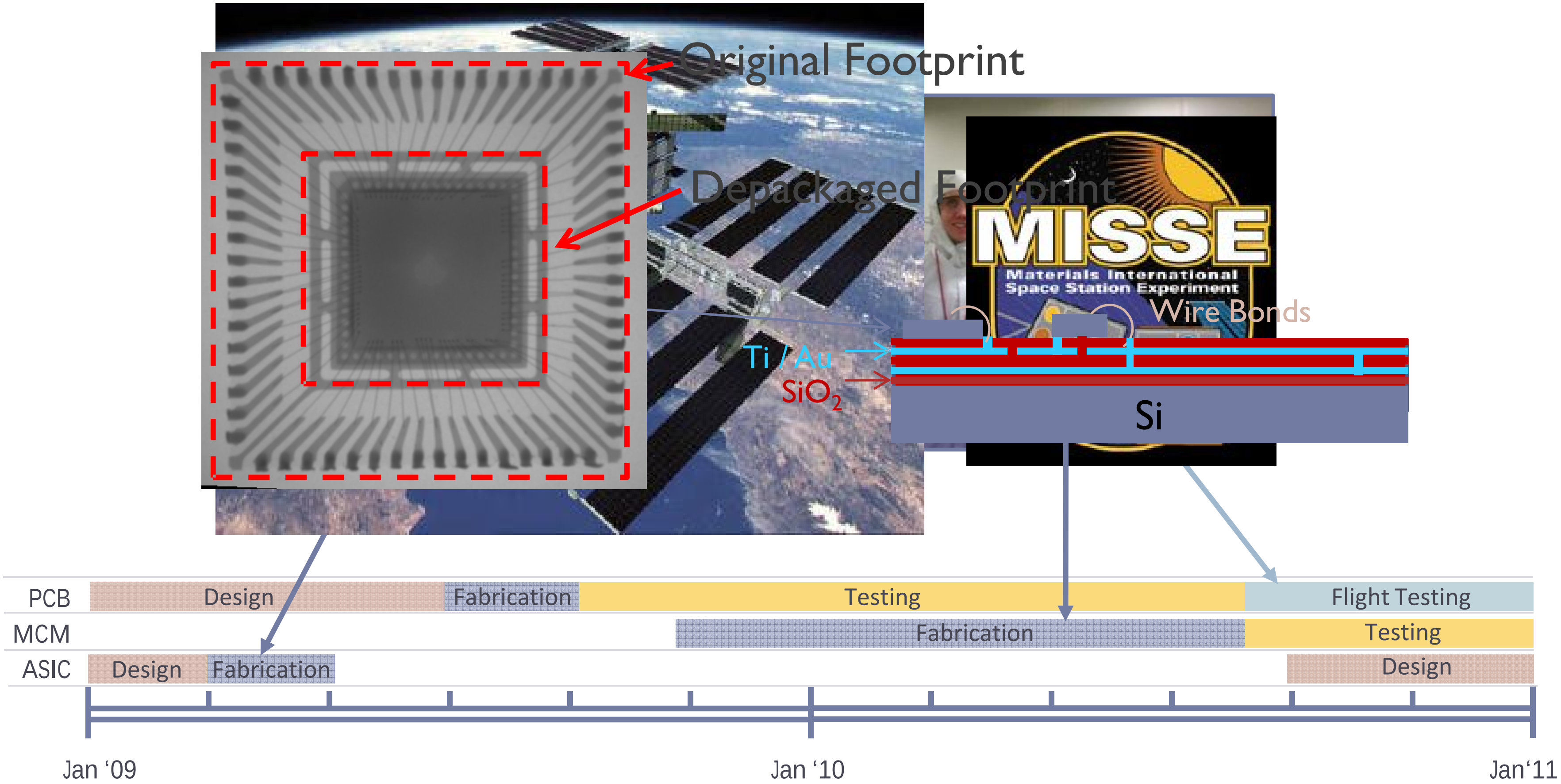




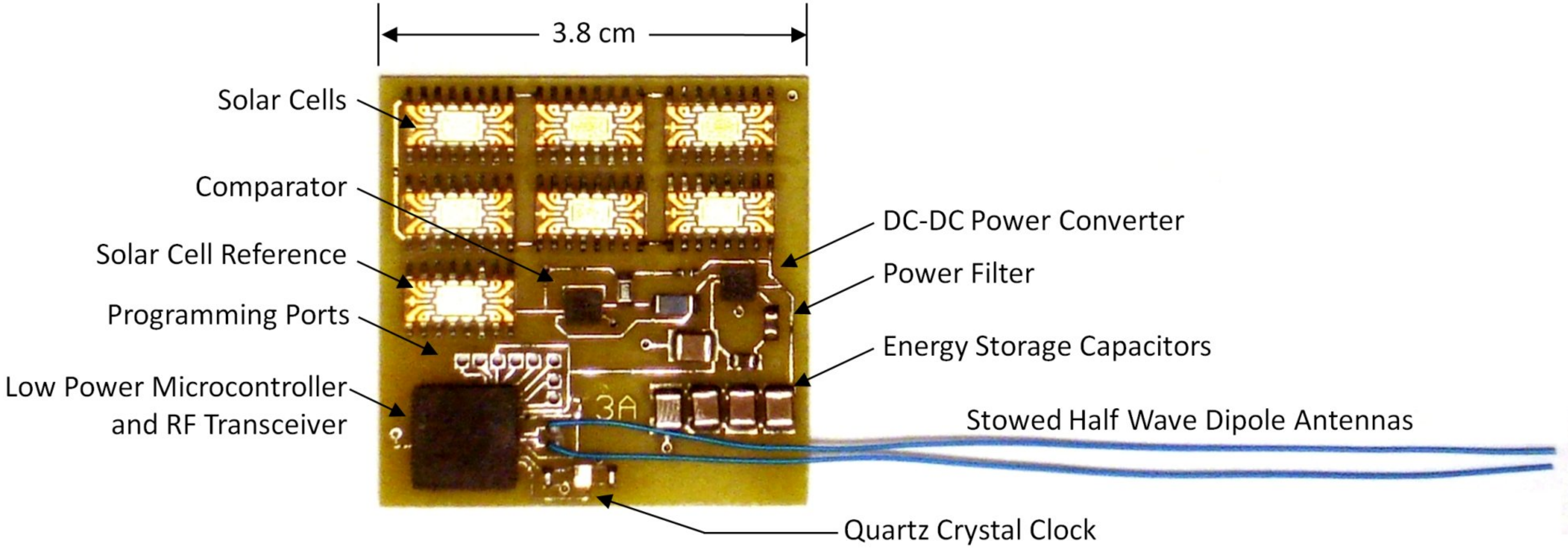
Sprite – Printed Circuit Board / Application Specific IC
A = 0.000[illegible] m^2
m = 0.00[illegible] kg
A/m = [illegible] m^2/kg

*All Images Courtesy NASA

Sprite Prototypes



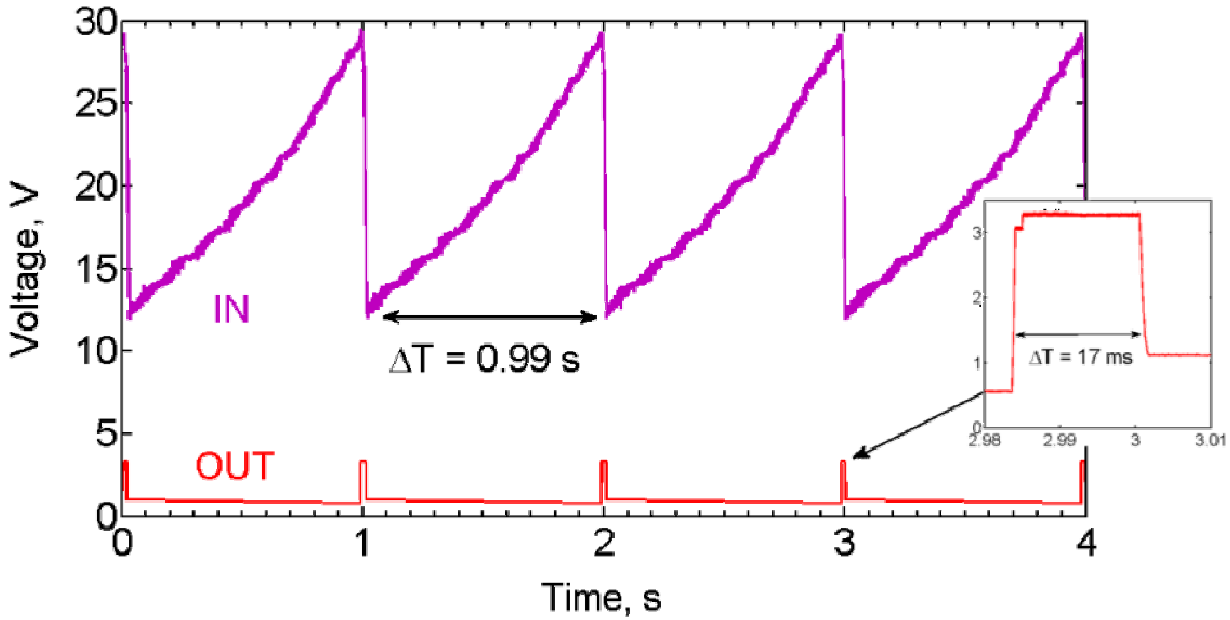
Sprite Features



Power Subsystem

“Bursty” Operation

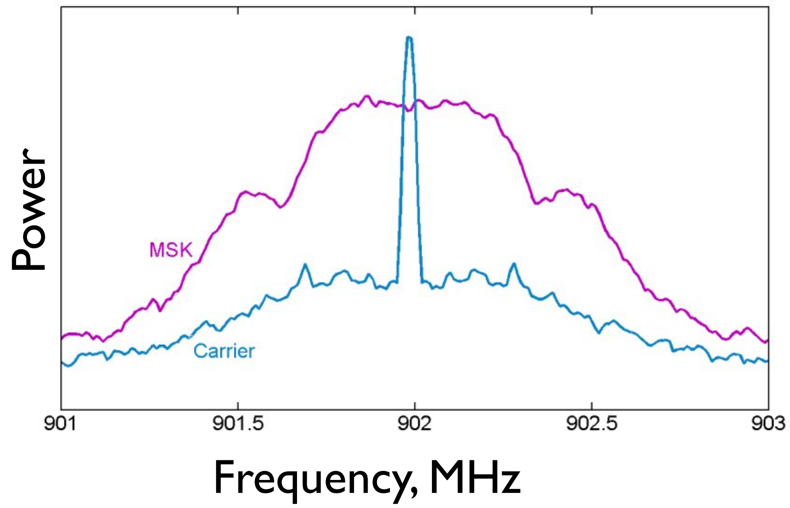
Solar cells charge a capacitor bank until there is sufficient energy to operate the microcontroller and radio.



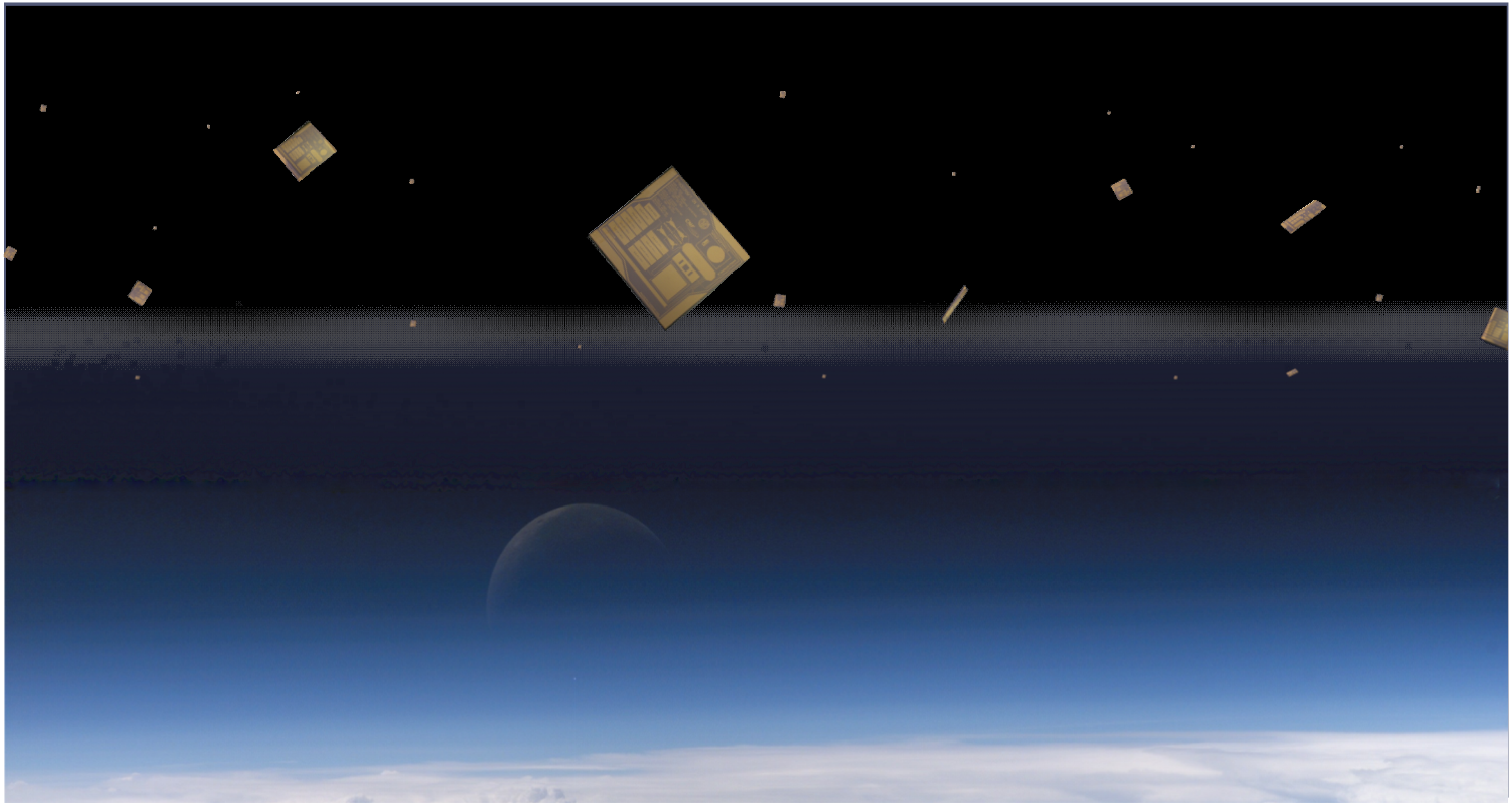
Communications

Matched Filtering

- The radio supplies only 12 mW
- 512 bit pseudorandom noise (PRN) sequence key for matched filtering offers ~30 dB of effective gain
- Minimum-Shift-Keying (MSK) for lower bit error rates



Atmospheric Sensors?



How Does Dust Survive Re-Entry?

Mechanical Forces*

- Magnitude of drag depends explicitly on *A/m*.
- Terminal velocity depends explicitly on *A/m*.
- Ram pressure goes with $\rho_A v^2$.

High-Temperature Ablation**

- There is sufficient kinetic energy to ablate.
- Small grains achieve uniform temperature quickly.
- Aerothermal heat-input goes with $\rho_A v^3$.
- Aerothermal heat-input is a function of the local flow properties.

Dust survives re-entry by shedding the majority of its kinetic energy in the rarefied atmosphere.

*Brownlee, D.E., *Ann. Rev. Earth Planet. Sci.* 1985.
**Whipple F.L., *Proc. Natl. Acad. Sci.*, [illegible].

Preliminary Aerothermal Model

A Skin Friction Coefficient C_F encapsulates the flow regime

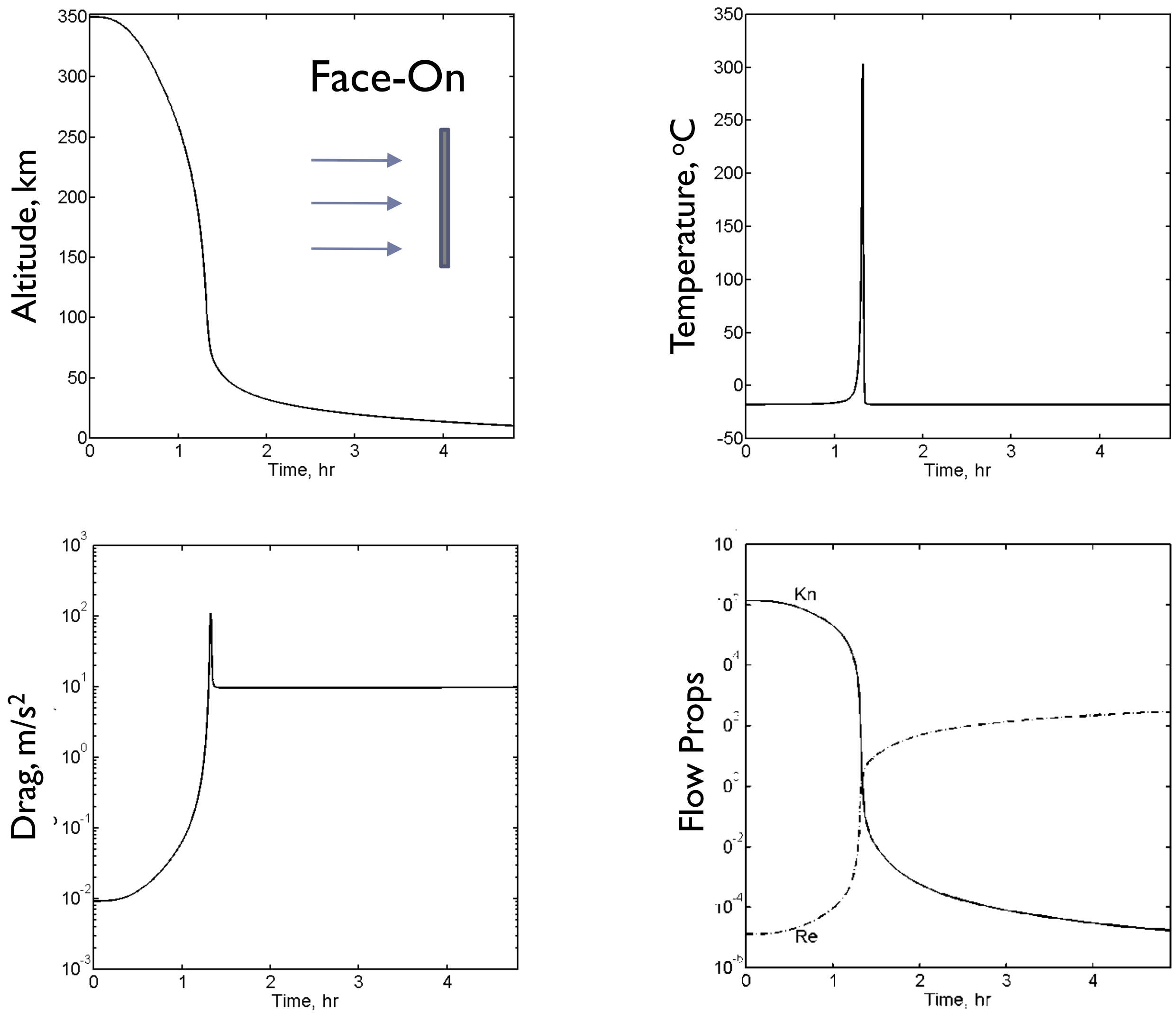
- Free-Molecular Flow*** ($10 \le Kn$)
- Transitional *** ($0.01 \le Kn < 10$)
- Continuum** ($Kn \le 0.01$)
  - Laminar ($Re \le 2300$)
  - Turbulent ($2300 < Re$)

$$Kn = \frac{\varsigma_A}{\lambda} \qquad Re = \frac{\rho_A v \lambda}{\mu_A}$$

$$\frac{dT}{dt} = \left(\frac{A}{m c_s}\right)\left[\underbrace{\frac{1}{4}\rho_{atm} C_F\left(Kn, Re\right) v^3}_{\text{Hypersonic Aerothermal Convection*}} - \underbrace{2\xi\sigma\left(T^4 - T_s^4\right)}_{\text{Radiation to Environment}}\right]$$

*Allen, H.J., and Eggers, A.J., "A Study of the Motion and Aerodynamic Heating of Missiles Entering the Earth's Atmosphere at High Supersonic Speeds," NASA Technical Report #1381, 1958.
**Hirshcel, E.H., Basics of Aerothermodynamics, 1st Ed, Springer-Verlag, Berlin, 2005.
***Koppenwallner, G., Fritsche, Band Bolts of Disintegrating Spacecraft during Uncontrolled re-entry", *Proceedings of the Third European Conference on Space Debris*, 19 - 21 March 2001, ., and T. Lips, "Survivability and Ground Risk Potential of Screws Darmstadt, Germany.

Ballistic Re-Entry Simulations



Conclusions

- Area-to-Mass is a design parameter that can drive spacecraft dynamics.
- For the right choice of area-to-mass and characteristic length, a body can re-enter while maintaining a low temperature.
- A spacecraft-on-chip architecture may be capable of demonstrating this low-temperature behavior.
- I welcome your advice on how to move forward with this analysis.

Acknowledgements

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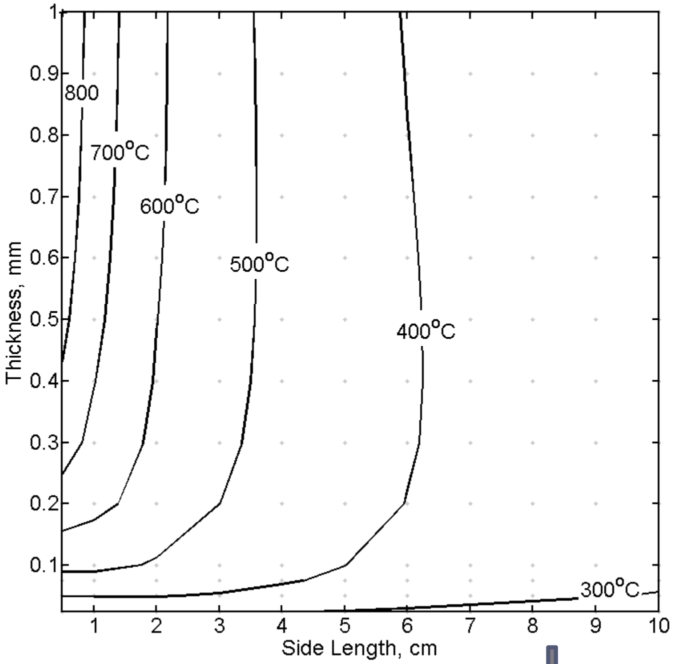
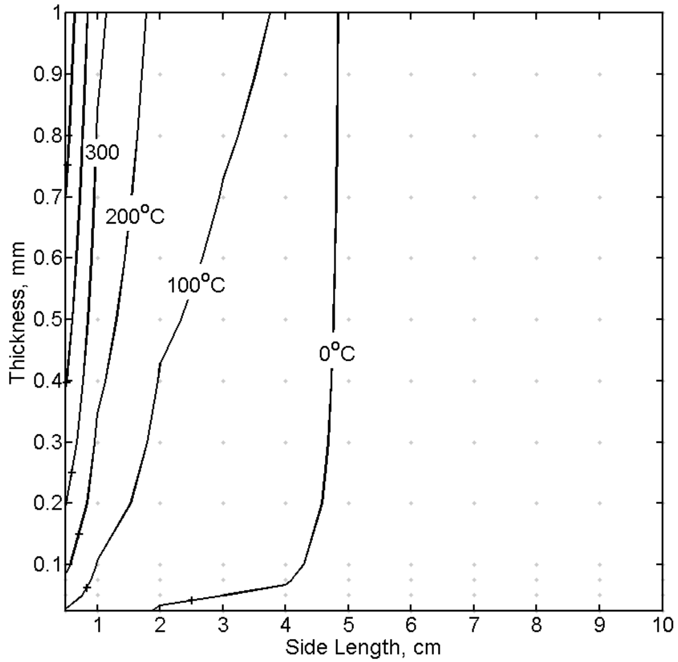
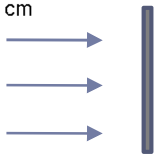
Parametric Search
Length and Thickness vs. Maximum Temperature

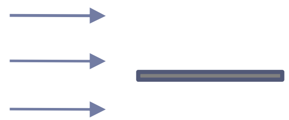




Face-On



Edge-On



Ballistic Re-Entry Simulations

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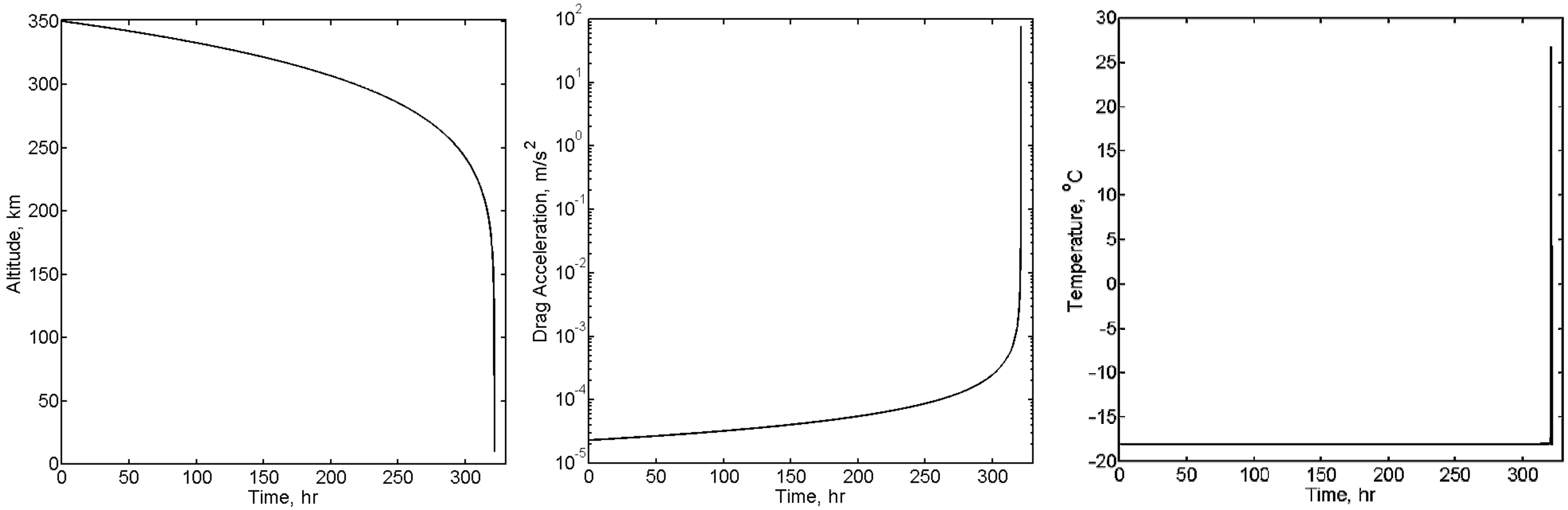
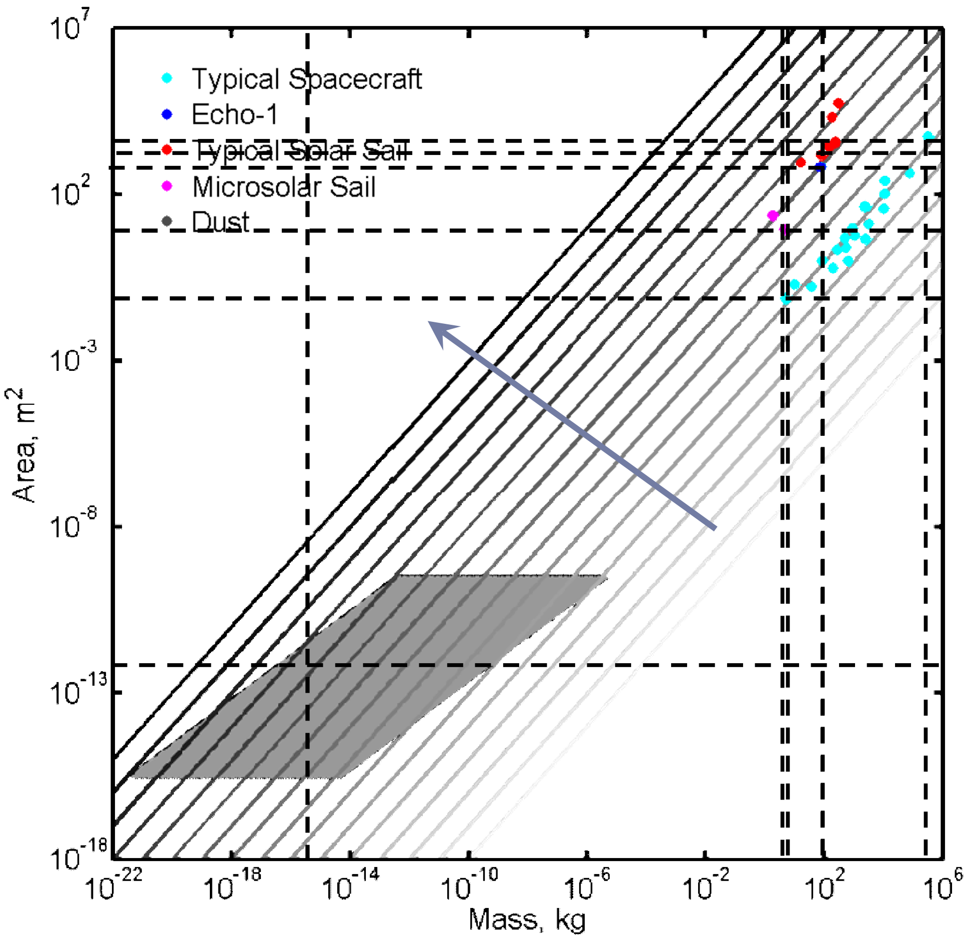
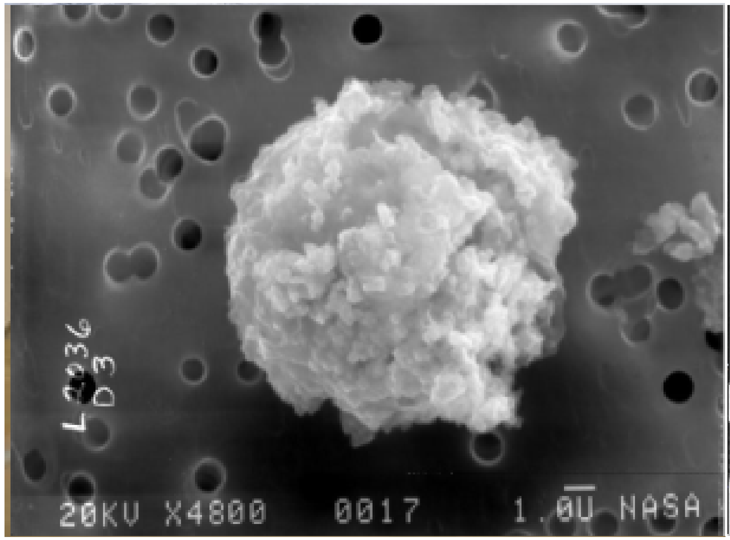
Sample Re-Entry Simulation

Edge-On, 1cm x 25µm



Survey of Area-to-Mass Values





[illegible] Station

A = [illegible]00000000078 m^2

m = [illegible]000000000052 kg

A/m = [illegible] kg

*All Images Courtesy NASA

Aerodynamic Drag

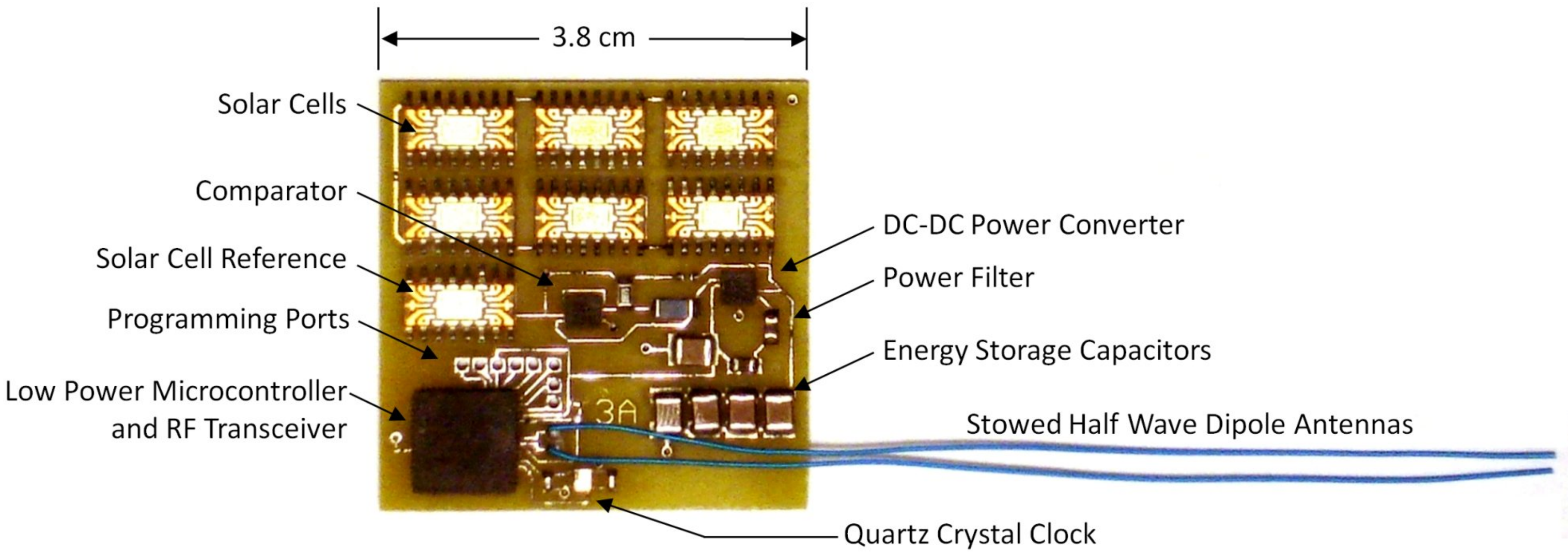
- Drag
  - Often characterized by the ballistic coefficient.
  - Typical spacecraft values fall between 10 and 100 kg/m^2.
  - A 1cm x 1cm x 25 μm silicon wafer achieves β = 0.02.
  - Ballistic coefficient drives terminal velocity.

$$\boldsymbol{a}_{AD} = -\frac{1}{2}\frac{A}{m} C_D \rho_A v^2 \hat{\boldsymbol{v}}$$

$$\beta = \frac{m}{A C_d}$$

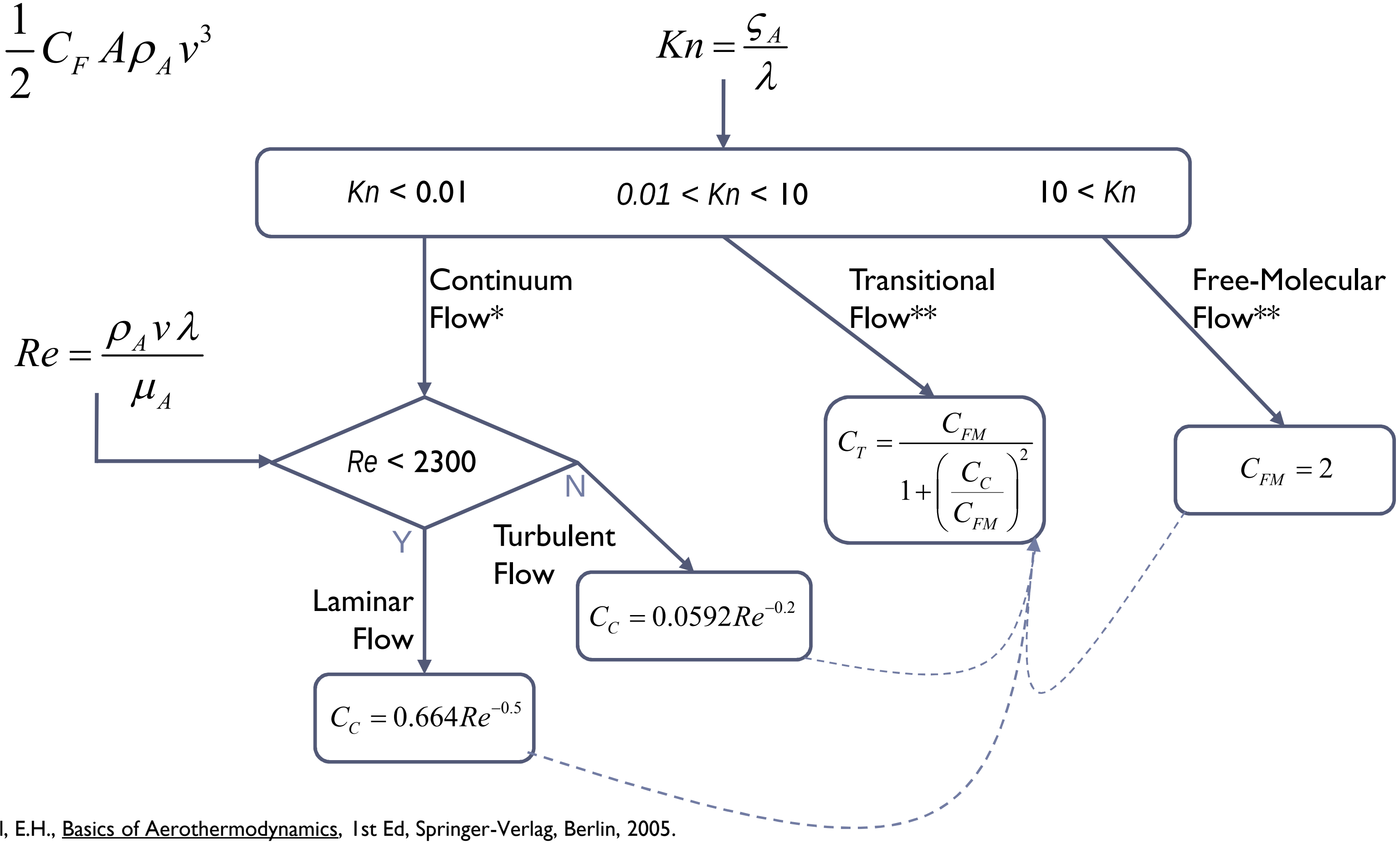
$$v_T = \sqrt{\beta \frac{2g}{\rho_A}}$$

Sprite Features



Skin Friction Coefficient

$$Q_c = \frac{1}{2} C_F A \rho_A v^3$$



* Hirshcel, E.H., Basics of Aerothermodynamics, 1st Ed, Springer-Verlag, Berlin, 2005.
**Koppenwallner, G., Fritsche, Band Bolts of Disintegrating Spacecraft during Uncontrolled re-entry", *Proceedings of the Third European Conference on Space Debris*, 19 - 21 March 2001, ., and T. Lips, "Survivability and Ground Risk Potential of Screws Darmstadt, Germany.

Sprite Power System

Parameter	Value	Units
Solar Cells	6	
Voltage	48	V
Current	50	μA
Capacitor	20	μF
Maximum Voltage	30	V
Minimum Voltage	18	V
Charge Time	1.0	s
Released Energy	6.4	mJ
Pulse Length	18	ms
DC-DC Efficiency	80	%
Filtered DC Output		
Supply Voltage	3.3	V
Supply Current	86	mA
Power Consumption		
Microcontroller Power	-0.6	mA
Transmitter Power	-29	mA
Margin	56	mA

Sprite Communications Subsystem

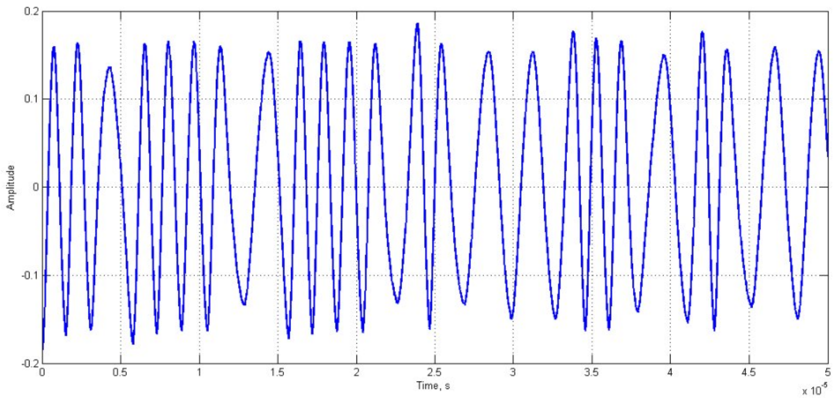
Parameter	Value	Units
Transmitter		
Power	10	mW
Antenna Gain	0	dB
Frequency	902	MHz
Bandwidth	1	MHz
Pulse Length	16	ms
Chip Rate	10	kHz
Orbit		
Altitude	500	km
Overhead Arc-Length	+/- 20	deg
Free Space Loss	-146	dB
Atmospheric Attenuation	-2	dB
Receiver		
Receiver Gain	18	dB
Noise Temperature	300	K
Noise Power	-142	dBW
Margin	5	dB
Received Power	-154	dBW
Carrier to Noise Ratio	0.07	
Matched Filter Gain	22	dB
Signal to Noise Ratio	11	

Communications

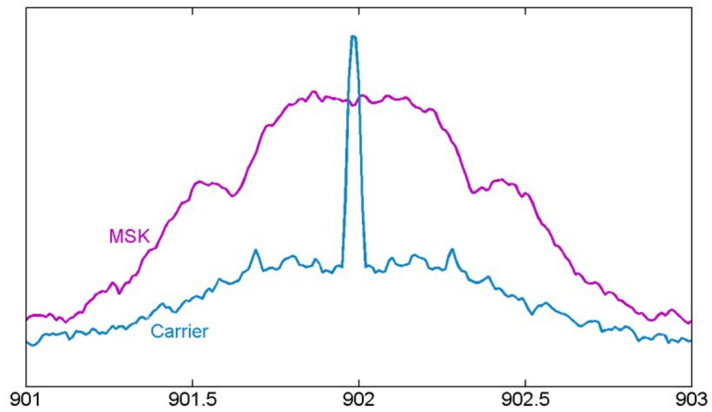
"Minimum Shift Keying" (MSK) Signal Modulation

MSK has the advantage of efficiently spreading the signal's energy over a range frequencies.

MSK Modulated Signal



Power Spectral Density



Angular Accelerations and Length Scale

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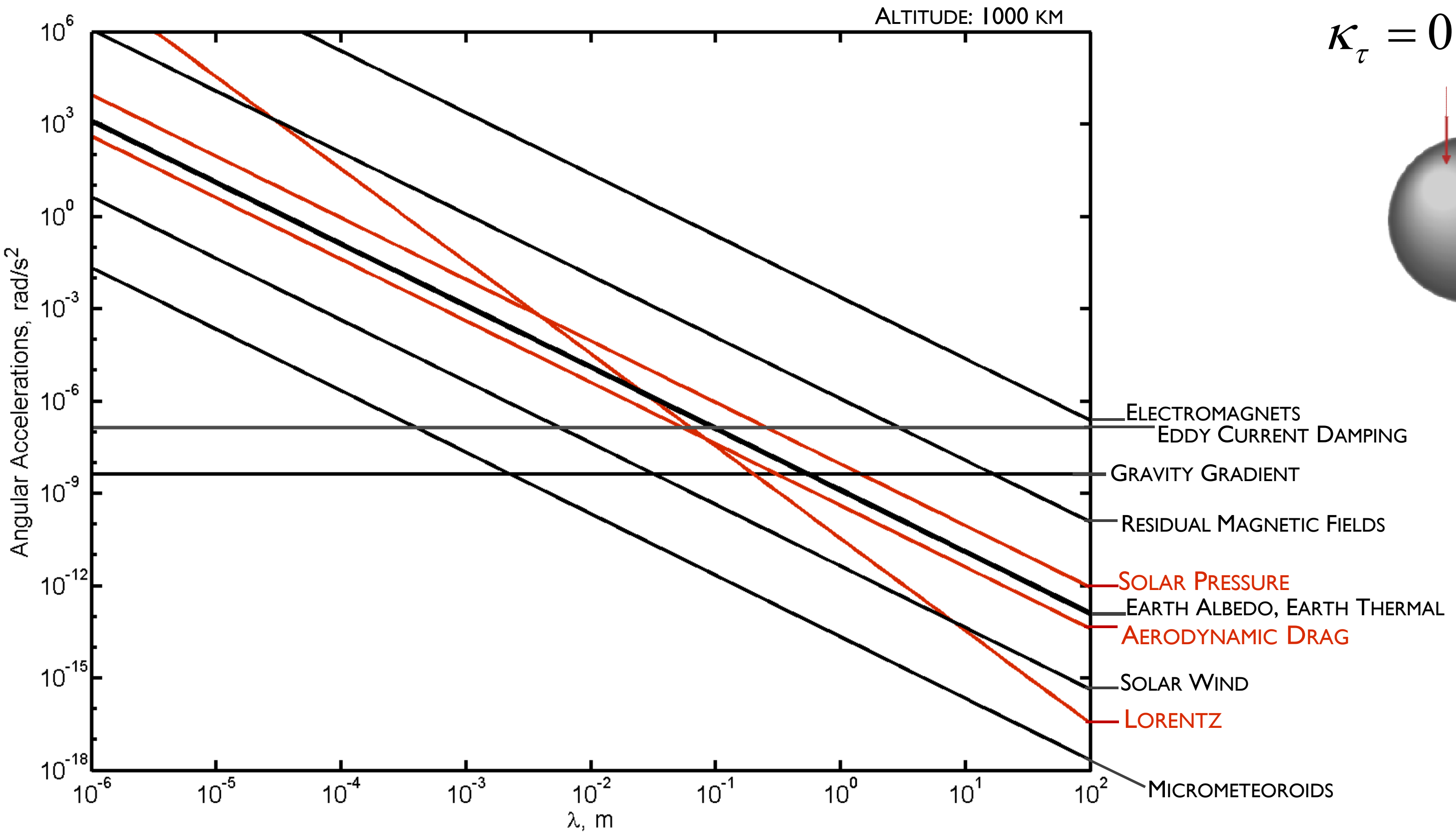
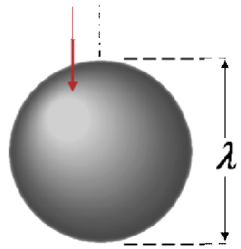


$\kappa_\tau = 0.01$



Concept Design Simulation **Conclusions**

↳ Backup Slides

Small Sensors

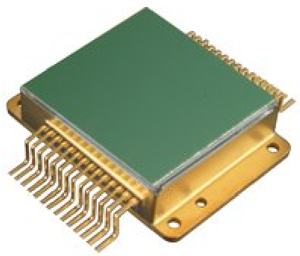
Miniaturization seems to be today's design paradigm.

"Mass is King"

CMOS Imager

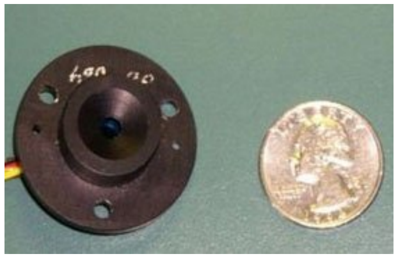
InvenSense 2-Axis Gyro

Kionix 3-Axis Accelerometer

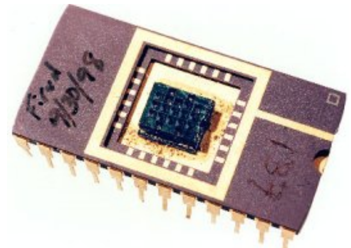


ULIS Microbolometer

Rockland Micromagnetometer



AeroAstro Medium Sun Sensor



DARPA Digital Micropropulsion